LOW-LOSS NbTiN FILMS FOR THz SIS MIXER TUNING CIRCUITS

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Abstract

Recent results at 1 THz using normal-metal tuning circuits have shown that SIS mixers can work well up to twice the gap frequency of the junction material (niobium). However, the performance at 1 THz is limited by the substantial loss in the normal metal films. For better performance superconducting films with a higher gap frequency than niobium and with low RF loss are needed. Niobium nitride has long been considered a good candidate material, but typical NbN films suffer from high RF loss. To circumvent this problem we are currently investigating the RF loss in NbTiN films, a 15K Tc compound superconductor, by incorporating them into quasi-optical slot antenna SIS devices.

Keywords: *NbTiN superconducting films, SIS junctions, Niobium bandgap*

I. Introduction

There is a strong astronomical interest to construct sensitive heterodyne receivers above 700 GHz, which is the bandgap energy of niobium. Niobium is the material of choice in nearly all Superconducting-Insulating-Superconducting tunnel junction (SIS) mixers. Niobium has a bandgap energy of (2Δ) of 700 GHz. Above this frequency the photons have enough energy to break Cooper pairs within the superconductor. This results in a very steep increase in the absorption loss of niobium films, as is shown in Figure 1. To circumvent this problem, up to 1.2 THz at least, we are developing quasi-optical SIS devices with NbTiN films[1]. Many of these devices show I-V resonances up to 1 THz, indicating that the loss continues to be low up to the gap frequency (1.2 THz). Comparison of circuit simulations and FTS measurements indicate that the resistivity of the NbTiN just above Tc is about 60 $\mu\Omega$-cm, which computes to a phase velocity of 0.21c for NbTiN microstrip lines with a 200 nm SiO dielectric. The critical temperature of the NbTiN films is around 15K and the gap voltage about 5.2 mV. Several different devices have been tested up to 650 GHz, all of which can be categorized in the following three groups.

-NbTiN ground plane, Nb wiring and Nb/Al-O_x/Nb junctions

-NbTiN ground plane and wiring, NbTiN/MgO/NbTiN junctions

-NbTiN/Nb ground plane and wiring, Nb/Al-N_x/NbTiN junctions

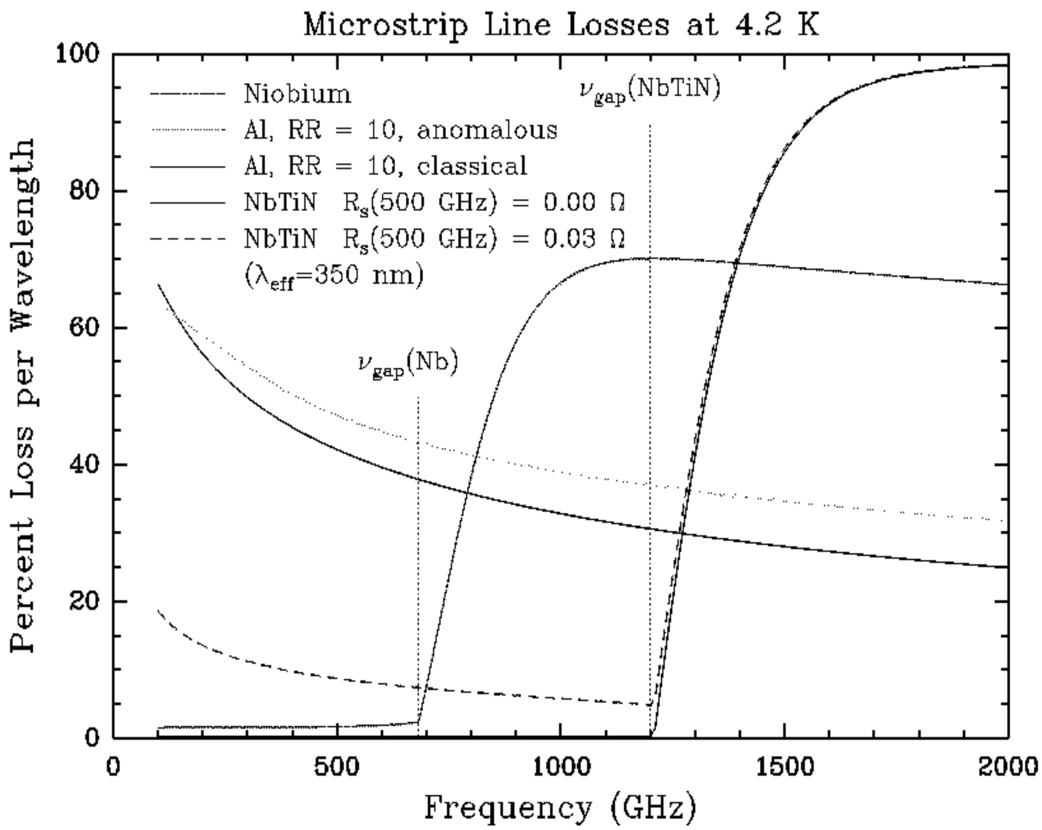

Fig. 1 RF loss of microstrip lines made with several different materials.

II. NbTiN Ground Plane, Nb Wiring and a Nb/Al-O_x/Nb Junctions

Since we did not know the material properties (mechanical and electrical) of the NbTiN superconducting films, we first fabricated double slot antenna devices with an existing mask designed for niobium [1, 2]. The devices had a NbTiN ground plane, Nb/Al-O_x/Nb junction, and niobium wiring. We have made direct detection Fourier Transformer Spectrometer (FTS) measurements and hot/cold heterodyne measurements near the peak of the FTS response, at 639 GHz. The frequency response measured with the FTS fits quite well with our circuit calculation if we assume that the NbTiN films have essentially no loss. Significant discrepancies arise between theory and experiment if the surface resistance of the NbTiN film is assumed to be 0.1 Ω/square. We also deduce from our circuit simulations a phase velocity of about 0.21c and a penetration depth on the order of 230 nm. For comparison, niobium films have a penetration depth of 80 nm. As an interesting side note, the heterodyne result of 110K at 639 GHz proved to be one of the most sensitive un-corrected receiver measurements at this frequency to date. Clearly the loss in the NbTiN ground layer is very low. A 9μm mylar LO injection beamsplitter was used during the duration of the heterodyne measurement.

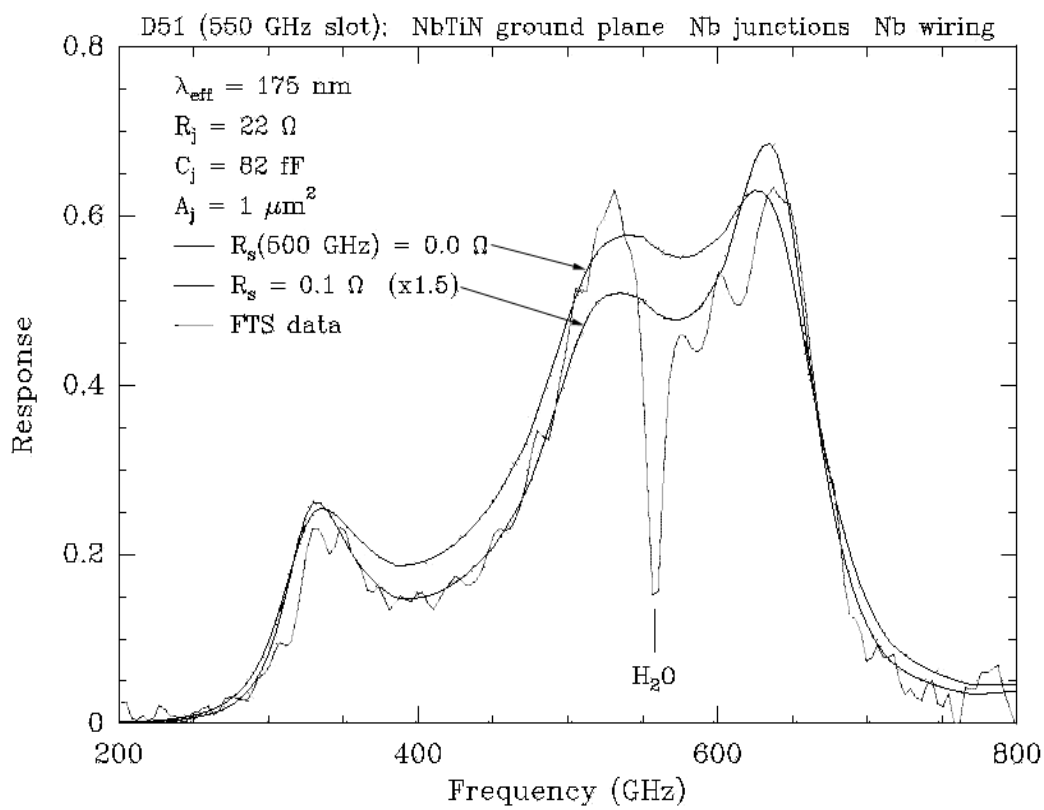

Fig. 2 FTS measurement of a Nb/Al-Ox/Nb junction with NTiN groundplane.

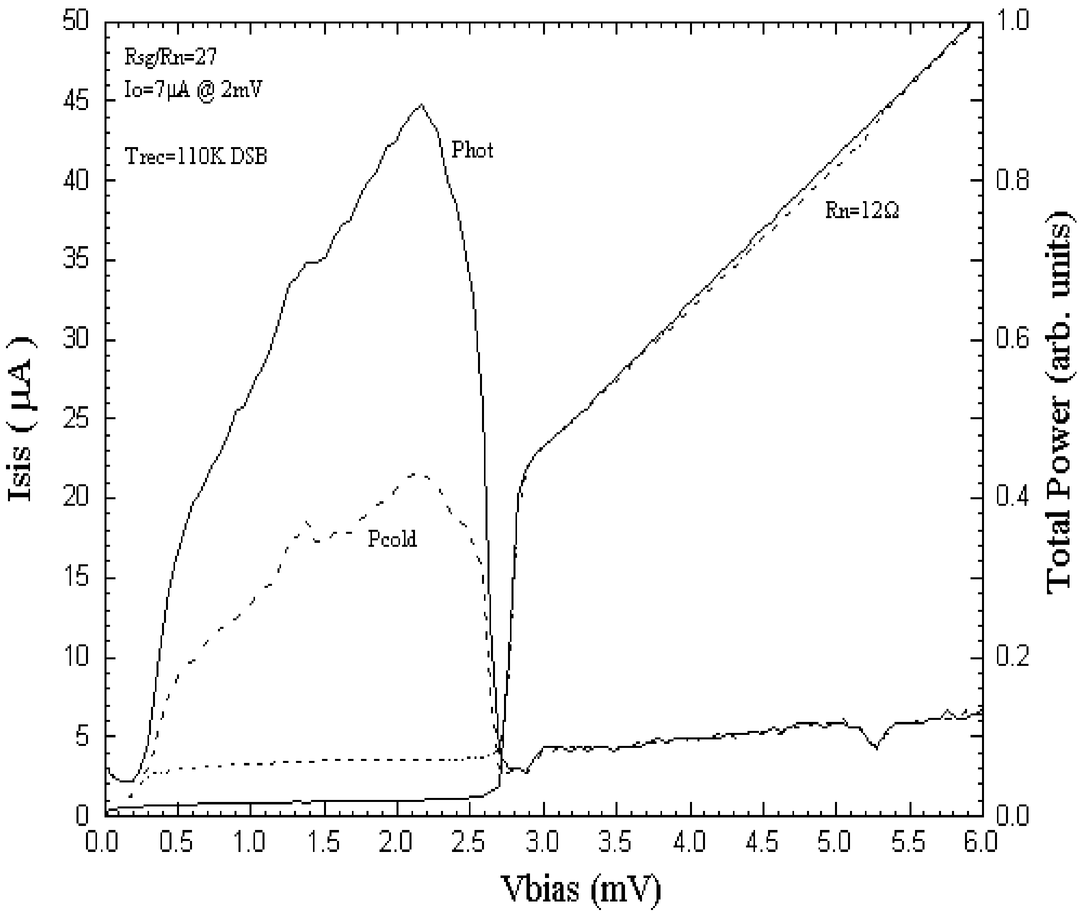

Fig. 3 Heterodyne response of a Nb/Al-Ox/Nb junction with NTiN groundplane at 639 GHz.

Once an understanding of the phase velocity and penetration depth of the NbTiN films was gained, we designed two different double slot antenna circuit layouts for further experimentation.

The first design was for an all NbTiN device with a NbTiN/MgO/NbTiN junction, and the second design was optimized for an Nb/Al-O_x /Nb junction. The difference being that, according to our computer simulations to FTS fits, the specific capacitance of a MgO barrier is on the order of 140-160 fF/μm^2. Nb/Al-O_x /Nb junctions with similar current density have a specific capacitance around 85 fF/μm^2.

The RF capacitive impedance of a 0.5 μm^2 NbTiN/MgO/NbTiN SIS junction at 1 THz is less than 2 Ohm, which makes it very difficult to match. Due to its lower capacitance, Al-O_x would be a preferred barrier except that we were not successful in fabricating high quality NbTiN junctions with Al-O_x barriers. A third barrier was used, Al-N_x, which has a reported specific capacitance similar to that of Al-O_x but is better suited to the fabrication process. There are good indications that Al-N_x has a lower barrier height than Al-O_x, and is thermally more stable.

III. NbTiN Ground Plane and Wiring, NbTiN/MgO/NbTiN Junction

As discussed, a 0.5μm^2 NbTiN/MgO/NbTiN SIS junction at 1 THz presents a mere 2 Ohm of reactance and the I/V characteristics are similar to the well known "washed-out" NbN I/V curves. Nonetheless, these devices are still of interest because of the relatively high energy gap, (2Δ) = 1200 GHz, and low RF loss. To verify that these films do indeed show improved performance over NbN devices, we have measured several of these devices over a wide range of current densities. Figure 4 shows the FTS response with three different circuit simulation fits for a junction with a RnA product of 42 Ω-μm^2. Though the fits are not perfect, it does enable us to put a upper limit on the loss (0.03-0.06Ω/square), get an estimate for the junction capacitance (132fF/μm^2 for a RnA product of 42 Ω-μm^2) and resistivity (60$\mu\Omega$-cm). We have also measured MgO devices with RnA products as low as 8 and as high as 60 Ω-μm^2. The specific capacitance, according to circuit simulations fits to the FTS data, for these particular device were 163 fF/μm^2 and 125 fF/μm^2 respectively.

The NbTiN/MgO/NbTiN SIS junction heterodyne measurement presented in Figure 5 has a receiver noise temperature of 250K DSB. This is several factors better than results reported with NbN devices at similar frequencies.

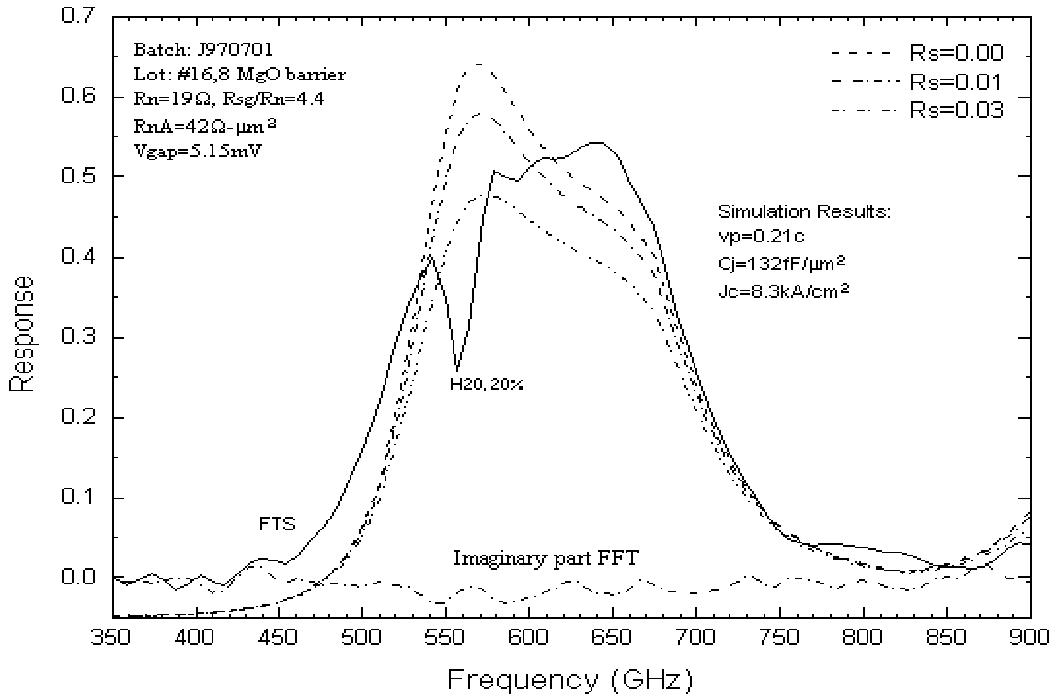

Fig. 4 FTS response of an All NbTiN junction with MgO barrier.

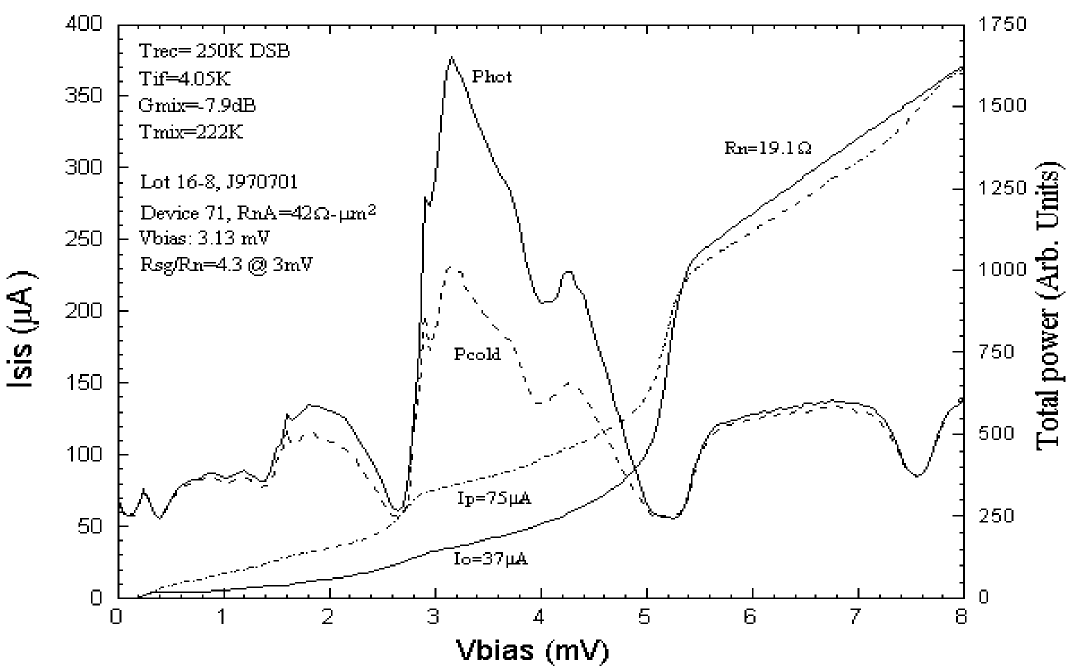

Fig. 5 Heterodyne response of an All NbTiN junction with MgO barrier at 638 GHz.

IV. NbTiN/Nb Ground Plane, NbTiN Wiring, Nb/Al-N_x/NbTiN Junction

A promising technology for THz applications is the use of an Al-N_x barrier rather than MgO barrier. This should result in a reduced specific capacitance, making the RF match to these evices at 1 THz more realistic. Josephson resonances in the I/V curve of many of these devices show resonances up to 2.1 mV. In Figure 6 we present a device that shows a rather nice resonance at 800 GHz. Unfortunately the I/V curve showed a weak-link break around 5 mV, and no heterodyne data is available for this particular device. Note that the junction gap voltage is at 3.5 mV. The devices discussed here were fabricated with a 100 Angstrom niobium layer on top of the NbTiN ground plane. This was done because Aluminum can readily be deposited on top of a niobium base electrode, but not easily on NbTiN. The sum gap of the 100 Angstrom niobium and NbTiN counter electrode is 3.5 mV as shown in Figure 6. Our calculations show that the absorption loss in the very thin niobium film is significant enough to effect the RF performance above 700 GHz, the gap frequency of niobium.

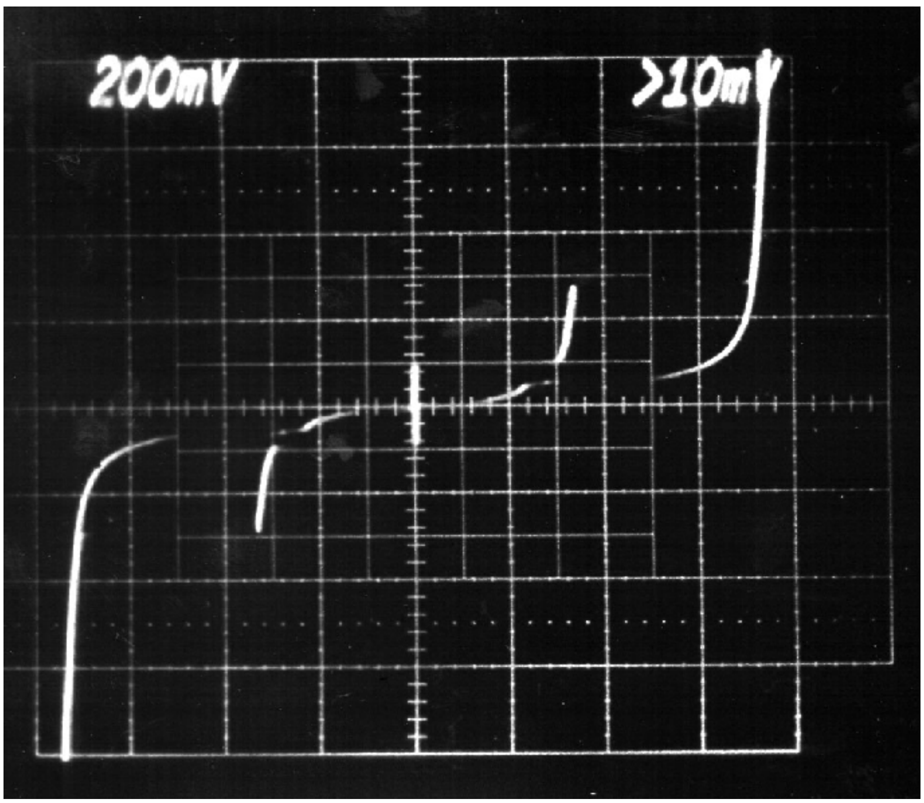

Fig. 6. Josephson resonance at 800 GHz of a Nb/Al-N_x/NbTiN junction
. Horizontal scale: 1mV/division, Vertical scale: 20µA/division

A new process is currently under development at JPL which will etch completely through the 100 angstrom niobium layer on top of the NbTiN base electrode, except for where the junction is patterned. This should solve the RF loss issue in the niobium film, yet still allow good quality IV curves with gap voltages around 3.5 mV. This technology is therefore particularly interesting for THz applications.

RF circuit simulations show a 3 dB bandwidth of about 120 GHz for these devices, which is in good agreement with the measured FWHM bandwidth of 115 GHz on our FTS. The small RF bandwidth is indicative of a low loss RF tuning circuit. In fact the 3 dB bandwidth of a similar device with aluminum wiring is 450 GHz [3].

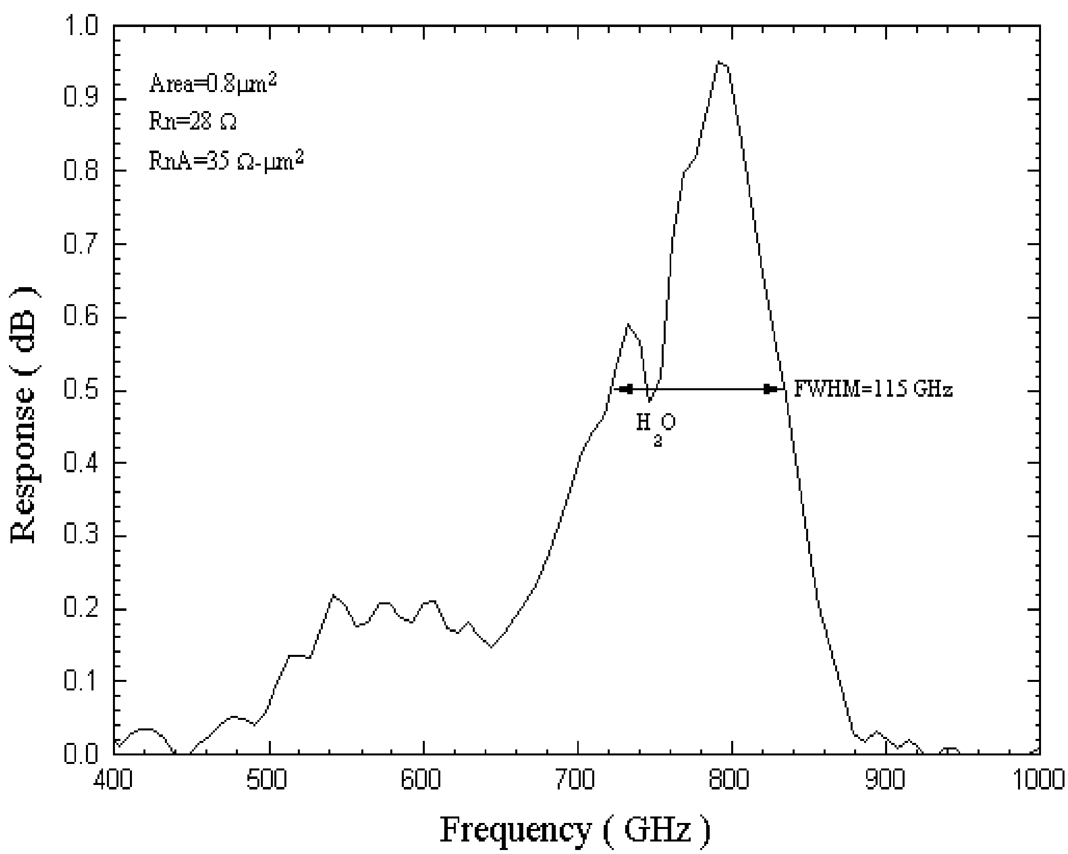

Fig. 7 Direct Detection response of a 950 GHz designed Nb/Al-N_x/NbTiN junction with NbTiN groundplane and wire layers.

Since no more high quality 950 GHz devices were available for this fabrication run, we turned our attention to a 650 GHz device. The direct detection response is shown in Figure 8. The measurement was made at two different resolutions and it shows a resonance that is shifted down from the 650 GHz design frequency to 590 GHz, approximately 10%. Heterodyne measurements at 588 GHz gave a 195K DSB noise temperature.

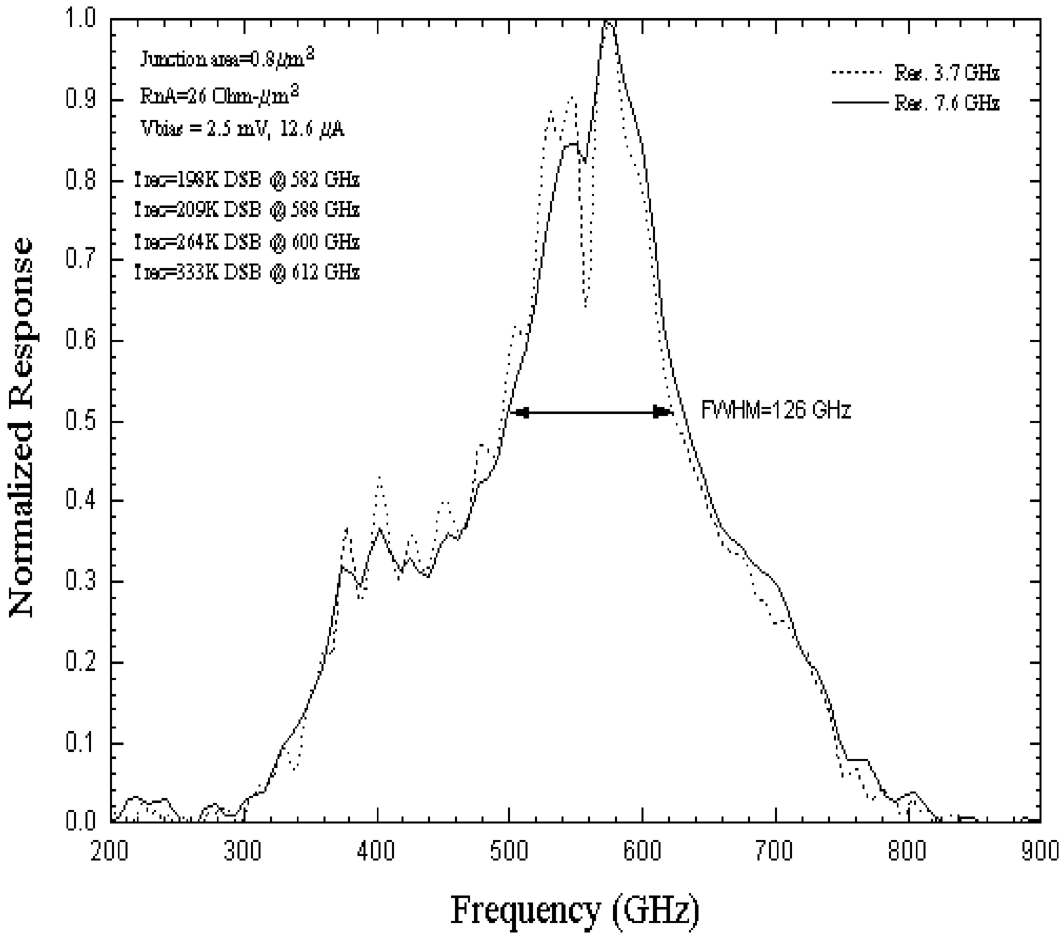

Fig 8 FTS response of an Al-N_x barrier junction designed to resonate at 650 GHz. RnA=26Ω-μm^2

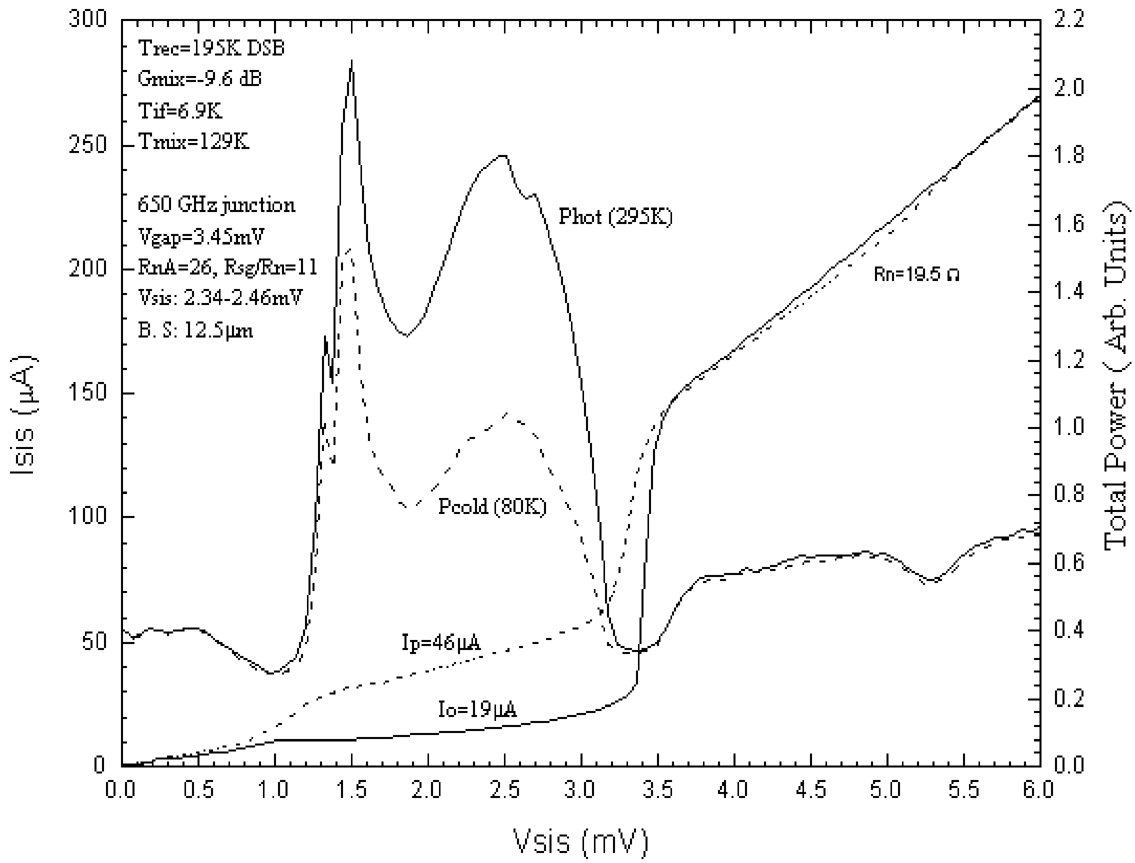

Fig 9 Heterodyne response if an Al-N_x barrier junction at 588 GHz.

The standard IF shot noise calibration technique[4] gave a mixer noise temperature of 129K and a mixer gain of -9.6 dB. The mixer conversion loss is somewhat higher than expected. The reason for this is not very clear since we are below the gap frequency of niobium. However if the loss in the NbTiN tuning circuit were significant would have expected a broadened RF response.

V. Conclusion

Clearly, our preliminary measurements demonstrate that NbTiN films show great promise for use in low-loss tuning circuits for SIS mixers at 1 THz. However, much work remains to be done to turn this promise into reality. Numerous technical difficulties must be overcome before a stable, reproducible fabrication process is available, which is necessary for the production of optimized devices. Several different junction configurations are currently under investigation as it is not clear which one will perform best up to 1.2 THz.

New devices have recently become available, and we anticipate testing them at 800 GHz in the very near future.

VI. Acknowledgments

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VII. References

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